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Compliance Control and Human-Robot Interaction: Part 1 - Survey

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Compliance control is highly relevant to human safety in human robot interaction (HRI). This paper presents a review of various compliance control techniques. The paper is aimed to provide a good background knowledge for new researchers and highlight the current hot issues in compliance control research. Active compliance, passive compliance, adaptive and reinforcement learning based compliance control techniques are discussed. This paper provides a comprehensive literature survey of compliance control keeping in view physical human robot interaction, e.g. passing an object, such as a cup, between a human and a robot. Compliance control may eventually provide an immediate and effective layer of safety by avoiding pushing, pulling or clamping in physical human robot interaction. Emerging areas such as soft robotics, which exploit the deformability of biomaterial as well as hybrid approaches which combine active and passive compliance are also highlighted.

Keywords: Compliance; Impedance ; Humanoids; Optimal Adaptive Control; HRI; pHRI

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1. Introduction

Compliance control schemes are often aimed to be used for safe physical human robot interaction (pHRI), e.g. object passing tasks. It should be made clear here, that compliance alone cannot ensure human safety in pHRI. This paper discusses research literature related to active compliance, passive compliance, adaptive compliance control, human robot interaction. The aim of this literature survey is to highlight the usefulness and application for active compliance control systems for human-robot interaction, e.g. passing objects between human and robot. This paper provides an overview of the already existing strategies for compliance control in this context. Compliance control research for safe HRI has recently attracted significant interest e.g. ^{15,25,91, 97, 59,98, 99}.

As mentioned earlier, compliance control can solve some of the safety issues in human robot physical interaction. This paper provides an extensive survey of compliance control techniques and provides a discussion on state of the art in compliance control. The main purpose of the paper is to highlight research activities in compliance control as well as to provide a good background knowledge to new researchers in human robot interaction (HRI). Hence, in the beginning of the paper (Section 2-4) it may be useful to define and briefly explain various types of force control techniques. In Section 4.2 active compliance research is discussed. Adaptive compliance control related work is reviewed in Section 5. In Section 5.1 reinforcement learning based compliance techniques are briefly discussed. In Section 7, recent trends in compliance control such as soft robotics are discussed. Towards the end, the paper is summarised and concluded in Section 8.

2. Direct Force and Indirect Force Control

Robot force control becomes very important when a robot is interacting with its environment, especially, where humans are in the co-space of a robot. Robot force control was initially a subject of interest for those machining operations in which a robot end-effector is in physical contact with its surroundings, for tasks such as polishing and grinding ^{102,103}. However, the importance of force control or its variants such as compliance control and impedance control has increased significantly because of their relevance in addressing safety issues in human-robot physical interaction.

There are two main force control schemes for robotic manipulators, i.e. direct force control and the approach of indirect control ^{88,87}. In the direct control scheme, a desired force is directly maintained between the environment and the robot end-effector by closing the force control loop. In indirect force control, force is normally maintained through position/motion control, without closing the force control loop ⁸⁷. Compliance control and mechanical impedance control are examples of indirect force control. Various types of force control are introduced as follows.

2.1. Impedance and Compliance

Mechanical impedance of a structure can be defined as the resistance to motion of a structure when an external force is applied. Mechanical impedance of a structure provides a relation between force acting on the structure and its velocity. Impedance at a specific point is determined in a structure by finding the ratio of the force acting on that point and the velocity of the point ⁶¹. Hence, the unit of mechanical impedance is Newton seconds per meter ($\frac{Ns}{m}$). Mechanical impedance is the inverse of mechanical admittance ⁸⁸. Mechanical admittance or mobility relates velocities of a point to the input forces. High mechanical admittance would result in faster motion for a given force in contrast to the high impedance which does the opposite ⁸⁴.

3. Hybrid Position/Force Control

In addition to direct and indirect force control (e.g., impedance control, compliance control), a third category of force control is hybrid position/force control, where in some directions a desired force is maintained while in the remaining directions, a position demand is tracked. Generally, these are the Cartesian space schemes in which the force control and position control tasks are split ⁶¹.

4. Compliance/Stiffness Control

Compliance control comes under the category of indirect force control and it is strongly similar in many ways to impedance control ⁸⁸. Research on compliance control dates back to 1976 ⁷². Active stiffness control ⁸⁰ is conceptually the same as active compliance control ⁸⁸. For instance, De Schutter ²⁶ has proposed a generic active compliance control scheme and investigated the role of passive compliance in active force control. In addition, he provided a useful discussion on compliance methods ^{80,45,38}.

There is a growing interest in research focusing on various issues involved in human-robot cooperation. Compliance control is highly relevant to the safety of humans in human-robot interaction. The human ability to vary its joint stiffness is probably the main reason for a human's successful interaction with its surrounding environment as well as the sense of greater safety in the pHRI ¹⁷.

There are two main methods to achieve compliance, i.e. passive compliance and active compliance control. Wang et al. ¹⁰¹ have compared active compliance and passive compliance for automated assembly systems. A comparison table from their work is included here in Table 1.

4.1. Passive Compliance

Passive compliance is the intrinsic flexibility in a robot manipulator inherited by its mechanical structure or by compliant actuators such as belt and pulley mechanism

Table 1: Active Compliance versus Passive Compliance¹⁰¹

Active Compliance	Passive Compliance
Mainly software based	Mainly hardware based
Easy to compute and regulate	Difficult to compute and regulate
Can be of general use	Normally, dedicated to an application
Compliance centre can be shifted	Compliance centre is normally fixed
Dynamic Compliance	Static compliance
Instability may occur	Overall stability is guaranteed
May be affected with kinematic singularities	Kinematic singularities problem is not applicable to passive compliance
Costly	Relatively cheap
Relatively simple structure	Mechanically more complex

or an artificial muscle. The behaviour of linkages has to be similar to a mass-spring-damper system for compliance. Beyl et al.¹³ have proposed a pneumatic artificial muscle for compliant actuation for a robotic application. A small robot using pleated pneumatic artificial muscles was developed by Beyl et al.¹³. The work by²⁹ discusses the use of agonist-antagonist actuation arrangement for a compliant actuation. They have produced laboratory prototypes of these arrangement. They have provided dependability analysis and failure detection in such systems. A recent article by Ham³⁶, gives a comprehensive review of the adjustable passive actuators. They discuss various types of passive compliant actuators such as pneumatic muscles, series elastic actuators and jack spring actuator etc. Choi et al.^{20 19} discuss the design of a passive variable compliance actuator using leaf springs.

Fig. 1: Small robot arm actuated by pleated pneumatic artificial muscles¹³.

4.2. Active Compliance

Active compliance can be achieved through the joint actuation of a robot via control. Torque or force feedback can be used to bring compliance to the manipulator. It is mainly software based and can be applied to different applications. A literature survey on active compliant motion can be found in the work by Lefebvre et al.⁶⁰.

Some of the early examples of controlling force via controlling the end-effector position or motion can be found in the work by^{46,45}. In these proposed motion and

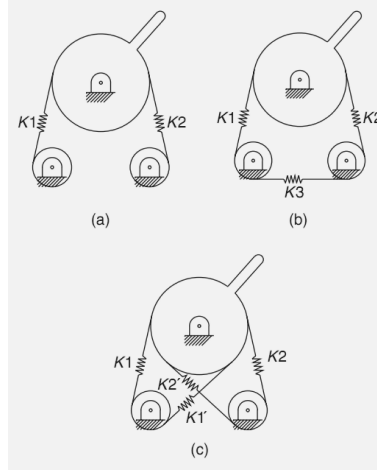


Fig. 2: Agonist-Antagonist arrangements (a) simple, (b) cross coupled, (c) bidirectional²⁹.

force control schemes, force is maintained via controlling position or motion.

Compliance control is very vital in industrial applications to handle objects and materials without damaging them. Komada and Ohnishi⁵⁰ have proposed an approach for compliance control of a multi degree of freedom manipulator. It is force feedback control, based on an acceleration controller. The work by Wu and Hwang¹⁰⁴ has suggested a nonlinear neuromuscular scheme for robotic compliance control of industrial robots. They have experimentally tested their suggested approach and found it successful. For example, in their study with single joint movements, the neuromuscular model can produce constrained and unconstrained motion and has the capability of adaptation for shifting between position control and force control. The neuromuscular model is emulating an agonist-antagonist arrangement.

Peng et al.⁷⁴ have worked on the compliant motion control of redundant manipulators. Their aim is to use the dexterity of their arm beneficially. They have proposed extended hybrid control and extended impedance control. In one example, Shetty et al.⁸⁶ have proposed an active compliant control strategy to control a Puma 560 robot. A compliance control scheme has been used by Kang et al.⁴³ for insertion of complex shaped objects into a hole. Al-Jarah et al.² have proposed and tested a compliance control approach in which the interaction force is reduced using a compliant quadratic cost function and compliance is expressed as a function of interaction force.

Kim et al.⁴⁷ have proposed a compliant control scheme for an unknown environment. The suggested scheme uses a self-adjusting stiffness matrix to adapt to various situations. A positive feature of this scheme is that it eliminates the switching of control strategies for unconstrained motion to constrained motion. Generally,

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switching from one controller to another may lead to instability. Albirchfield et al ⁶ (see also ^{4,5}) considers a self-adjusting active compliance control for multiple robots handling a flexible object. This is an active compliance scheme using a mathematical model of the object to be handled. Moreover, the dynamics of the arms are also used for the position control.

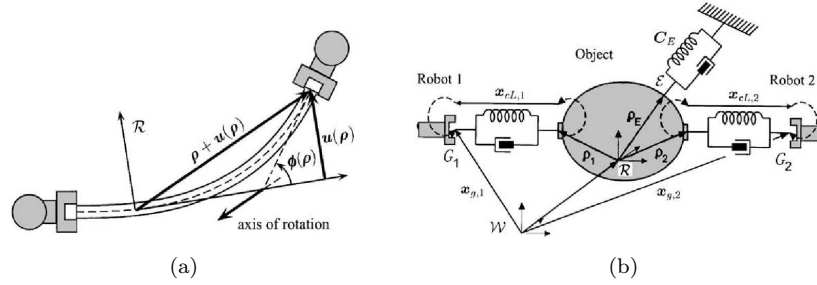


Fig. 3: (a) Elastic displacement of the object (b) virtual object with concentrated compliance ⁶.

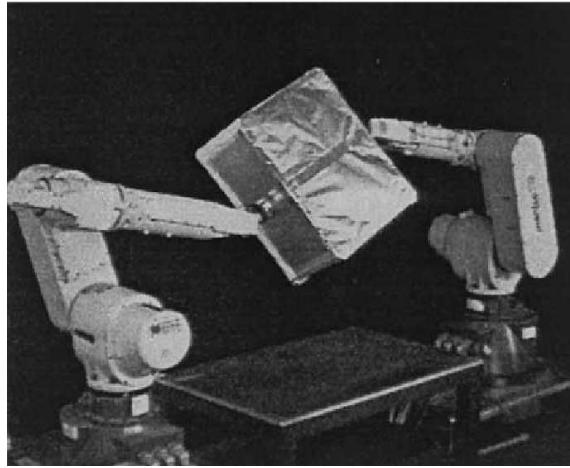


Fig. 4: Experimental setup (using two Puma 560 robots) ⁶.

Zollo et al. ^{111,114,94} have reported compliant control of a humanoid robot arm using cable actuation. The robot arm on which the proposed control scheme has been tested is an assisting robot to help a human in everyday life. They have suggested two different control schemes, i.e., compliance control schemes with self-regulating compliance in both the Cartesian space and in the joint space. Both of

these strategies enable the robot to adjust its compliance in free space as well as unplanned constrained motion without using the contact forces or robot dynamics model. They do not use inertia matrix information and Coriolis/centripetal torques, however, they use the gravity part of the dynamic model. The control law consists of a PD control law plus the gravity torques or forces. Compliance is varied by using a self-controlled exponential function. This compliance function controls the value of the proportional gain, and varies exponentially with the Cartesian position error (for the Cartesian scheme) or joint error (in case of the joint space scheme). In their case, cable actuation also provides some passive compliance.

A third scheme proposed by Zollo et al.¹¹³, is an impedance compliance control for a cable actuated robot arm. The scheme is similar to the Cartesian space scheme in^{111,114}, however, they created two sub-systems; one sub system (using three joints) of the robot has a Cartesian impedance control, and the other sub-system (using four joints) has a Cartesian compliance scheme. In this case, the overall scheme is more dynamic model dependent and works better than the two strategies mentioned in the preceding paragraph. In the article¹¹⁰, they provide further details on the above mentioned three schemes^{111,114,94},¹¹³. They concluded that these three proposed schemes work well in the human environment as far as safety is concerned. It is claimed that the compliance control in the joint space and impedance-compliance control is functionally better as these can work in the entire work space (see also the work by Zollo et al.¹¹²). Here, it should be made clear that all these approaches are based on the idea of a robot with elastic joints and some of the schemes are partially dynamic model based and some are fully model based schemes.

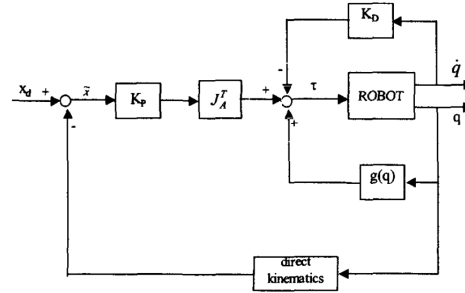


Fig. 5: Compliant control scheme in Cartesian space¹¹¹.

The compliance control scheme of^{31,30} is similar to the schemes of^{111,114,110} mentioned above, however, they have employed the torque sensor feedback and use a linear relationship between torque and joint stiffness. The compliance control scheme in the the joint space scheme is proposed for the robotic motor therapy machine. In this particular example, the suggested control strategy is intended to help and guide patients in the execution of motor tasks. The effectiveness of the

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scheme has been tested in simulation only. The block diagram of the scheme is shown in Figure 6.

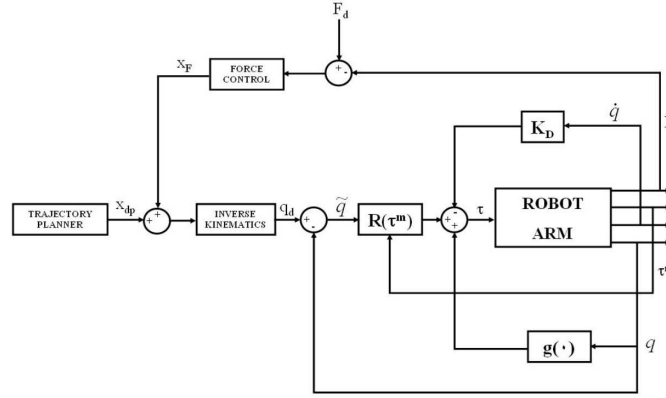


Fig. 6: Block diagram of the torque-dependent compliance control scheme ³¹.

Bichi and Tonietti ¹⁴ have concluded that compliance cannot be perfectly achieved unless the mechanical structure of the robot has inherited compliance capabilities. They are convinced that compliance should be introduced at the design level. In this particular example, passive compliance (mechanical) has been introduced into the system and an advanced control scheme has been used to recover the accuracy. Note that for the compliance controller, is not suitable for the robots whose design does not cater for passive compliance. In general, it is good to have some degree of passive compliance for safety.

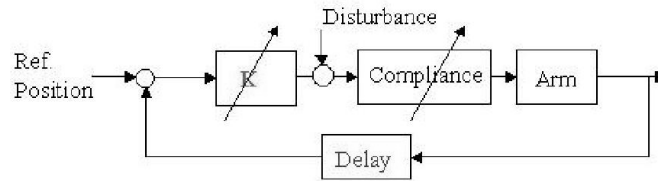


Fig. 7: Passive or mechanical compliance has been introduced in the system on purpose to ensure safety ¹⁴.

Zinn et al. ¹⁰⁹ have developed a new actuation scheme termed as the distributed macro mini (DM^2) actuation approach to address safety issues. This approach has been developed to overcome the limitations of existing approaches, such as the *joint torque controlled actuation* approach of ¹⁰⁰ and the *series elastic actuation* approach of ⁷⁷. In this method, the major source of actuation effort is relocated

from the joints to the base of the robot manipulator. For this, the torque generation is divided into low and high frequency actuators. Manipulation tasks which entail position or force control require a low frequency response while disturbance rejection uses a fast frequency. Both of these high and low frequency actuation schemes must have negligible impedance for the approach actuators to work. Secondly, the DM^2 actuation approach involves coupled actuation (parallel coupled macro-mini actuation approach). In this way, low and high frequency actuators are distributed to the locations on the manipulators to minimize the effect on contact impedance and the gain of the control bandwidth is maximized. Sardellitti et al.⁸¹ propose an air muscle controller using the DM^2 approach.

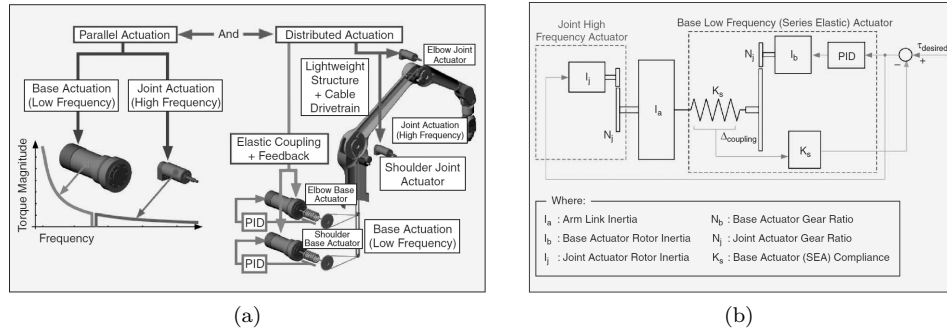


Fig. 8: DM^2 actuation¹⁰⁹.

Zhang et al.¹⁰⁷ have employed a force feedback active compliance control strategy for a humanoid robot arm, which has a six-axis force-torque sensor installed in the wrist. When the robotic arm physically interacts with the environment (grasping an object), the sensor feedbacks the magnitude and direction of the interference force. When the interference force exceeds a certain threshold, an active compliance control is switched on to compensate the interference force.

Ott et al.⁶⁷ have used a very interesting approach in which they have decoupled the actuator dynamics from the robot dynamics. The controller has two loops. One is the inner control loop which controls the actuator output torque; and the outer loop controls the robot. The inner loop here decouples the torque's dynamics from the rigid body dynamics. The overall approach is a Cartesian impedance controller for a flexible joint robot. The scheme is similar to the work by Bichi et al.¹⁴.

Koeppel et al.⁴⁹ have discussed compliance control of the DLR light weight robot. They argue that human-like compliant behaviour can be achieved using a combination of a serial manipulator equipped with sensorized joint actuators and control. The research being carried out at the DLR institute in Germany is a step ahead in the compliance control of robot arms^{9,10,8}. The robotic platform developed at the DLR has good intrinsic compliance capabilities. They have proposed and

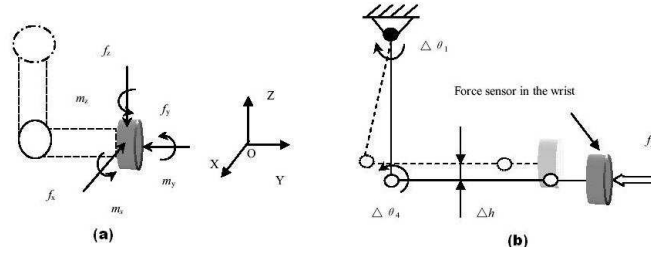


Fig. 9: (a) Six-axis force-torque sensor in the wrist (b) simple model of the arm by y-axial force ¹⁰⁷.

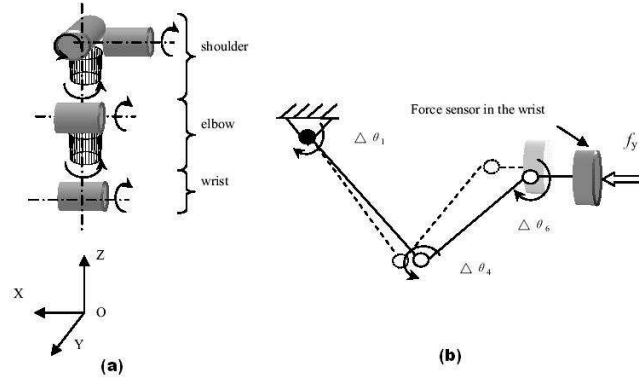


Fig. 10: (a) Model of the humanoid robot arm (b) the representative moving model ¹⁰⁷.

tested compliance control strategies which have brought greater safety in the use of such robotic platforms. One of the key steps is the zero gravity mode, i.e. the robot behaves as if it is in a zero gravity field. A Cartesian impedance control has been implemented in these robots.

Albu-Schäffer et al. ⁷ have discussed the torque dependent active compliance control approaches based on passivity theory. They also stress on the importance of passive actuators and intrinsic compliance. The article by Albu-Schäffer et al. provides a good summary of the progress they have made in this regard at the German DLR Institute over the last decade. The research at the DLR Institute provides a good launching pad for new area of soft and safe robots control and design (see for example, ^{68,69,57,71,70}).

The techniques they have used are more platform dependent and exploit the inherent compliance of their robotic system and a good knowledge of the robot parameters and dynamics. The work in DLR gives a good insight into the safety issues and their possible solutions. However, one cannot solely rely on these techniques if

a robot arm design lacks passive compliance capabilities.

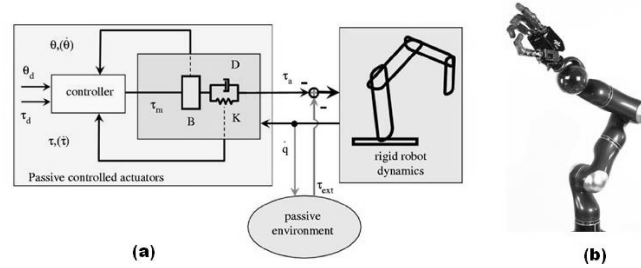


Fig. 11: (a) Structure of the joint level controller (b) DLR light weight robot arm with hand ⁸.

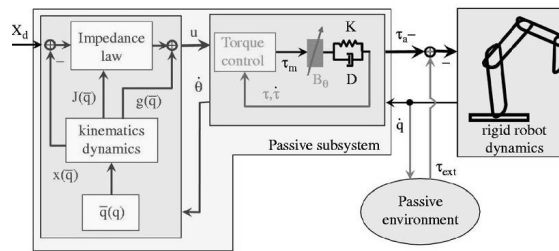


Fig. 12: structure of the cartesian impedance control ⁸.

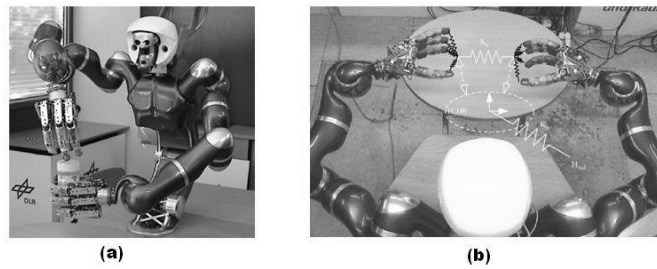


Fig. 13: (a) the DLR humanoid manipulator justin unscrewing a can (b) two-hand impedance behavior based on combination of object-level impedances of the hands and arms ⁸.

Jin et al. ⁴¹ have proposed a robust compliant control technique with nonlinear friction. This technique uses time delay estimation for cancelling out soft nonlin-

earities to decrease the effect of hard nonlinearities. They are using ideal velocity feedback. This approach provides on-line compensation for friction without modelling it.

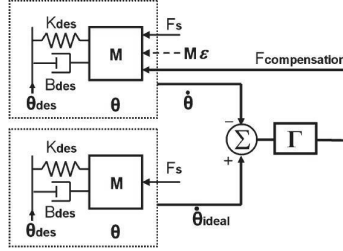


Fig. 14: Ideal velocity-feedback-compensation concept ⁴¹.

5. Adaptive Compliance Control

Adaptive control is more than half a century old; nevertheless, there is significant interest in the field, due to its success in real time applications where model based controllers would not produce the desired results ^{82,90}.

In the previous section, some of the research on compliance control and its applications have been discussed. However, the reviewed approaches are dynamic model based, and dynamic models are usually prone to uncertainties and un-modelled nonlinearities. Moreover, dynamic models for more than 2-3 DOF become very complex and large. In a model based control, many strict assumptions (e.g., ignoring friction and stiction, assuming masses, sizes and shapes of links etc.) are made to simplify the modelling process, which may reduce the effectiveness of the control algorithm based on such a simplified model. Hence, to overcome the uncertainty in model parameters as well as changing loading conditions, adaptive control is a desirable choice.

Adaptive control has a long history; work on adaptive control started in the 50s when control engineers had to deal with the problem of autopilots for fighter jets ⁹². Astrom ⁹³ provided a brief but an excellent survey of the important developments, which took place in the field of adaptive control around the 1960s.

There are two main types of adaptive control schemes, i.e., *model reference adaptive control (MRAC)* and *self tuning (ST) adaptive control*. Self tuning control can be further classified as either direct or indirect adaptive control ⁹⁰.

Some work has already been done on adaptive compliance control for robot manipulators by various people around the world. In this section, some examples will be presented. The area of adaptive compliance control has been a field of interest for many researchers. However, the context of the early research was to solve industrial problems such as machining and assembly operations like grinding and insertion of

one component into another. These tasks generally occur in the highly controlled and structured environment of industry. For instance, the work by Niemeyer and Slotine^{65,66} proposed a computational algorithm for an adaptive compliant control scheme. They assume that the contact environment is passive. The suggested control scheme is an adaptive impedance controller in which a force-to-velocity mapping has been used. The scheme involves switching between a force and a position control scheme when the interacting robot surface (i.e. the end effector) changes from a parallel to perpendicular orientation with respect to the object of interest. In the context of HRI, this controller switching and dependence on direction may limit the applicability in a human environment, which is highly unstructured. It is also not certain if stability can be guaranteed when switching between the two strategies in the social multi-directional human environment.

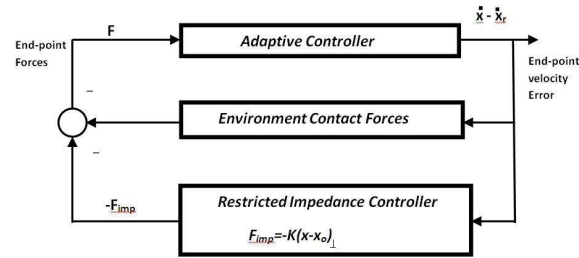
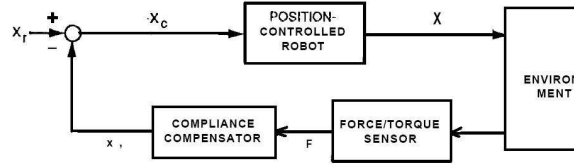


Fig. 15: Adaptive compliance control systems^{65,66}.

The work of Peltier and Daneshmand⁷³ has reported an adaptive compliance control strategy based on damping control. The scheme uses an MRAC-based strategy when the robot interacts with the environment. If it is in free space then the adaptive control is switched off.

Seraji⁸⁵ has proposed an adaptive compliance control approach for robot manipulators. It is a position based implicit force control system. More specifically, the work by Seraji uses a reference position to control the contact force. The environment has been modelled as a linear spring. He presented two different schemes, namely a stability-based adaptive compliance compensator and an MRAC-based adaptive compliance compensator. Similarly, Colbaugh et al.^{23,22} (see also²⁴ for an advanced formulation) have suggested two model-free adaptive compliant control schemes for rigid link manipulators. The first one is an adaptive impedance controller. In this approach, the impedance of the end effector is ensured via an MRAC scheme guaranteeing a passive reference system. The second scheme is an adaptive position/force controller in which the end effector's space is separated into the direction in which the end effector can move and the direction it is exerting force. The controller then ensures the desired values of force and position in the corresponding directions. This scheme has similarities to the work by Niemeyer and

14 *Said G. Khan*Slotine^{65,66}.Fig. 16: Position based adaptive compliance control systems⁸⁵.

Yang et al.¹⁰⁶ have suggested an adaptive position/force controller for a robot manipulator with compliant links. The adaptive controller is based on a reduced dynamic model and singular perturbation theory. They decompose the original system into two time-scale systems, i.e., slow subsystem and fast subsystem.

Siciliano and Villani⁸⁹ have implemented an adaptive compliant control scheme which is based on a vector composed of velocity error, modified position error and the integral of the force error. During interaction, if there is any conflict between the position and the force error, priority is given to the force action. The contact environment is assumed to be an elastic frictionless surface. In this method, position, velocity and force feedbacks are mandatory. Further, the force error and position errors are interdependent.

Ham³⁷ has proposed an adaptive force/position control of a robot manipulator based on hyper stability. The controller is based on the passivity of the robot. He assumes that the end effector has a force sensor which is modelled as a linear spring.

Roy et al.⁷⁹ have researched the area of adaptive control of position/velocity controlled industrial robots and proposed new adaptive compliance schemes. The schemes are implicit force tracking schemes based on the velocity. One of the schemes assumes that the compliance of the environment is known. The other scheme learns the compliance of the environment adaptively. They provide a global asymptotic stability proof for their suggested schemes.

Chien and Huang¹⁸ have proposed an adaptive impedance control scheme which is based on the function approximation technique. This method is unlike other commonly used adaptive control methods, as it does not use a regressor matrix. The suggested scheme does not need acceleration measurement or the inverse of the inertia matrix. Jiang¹⁰⁸ has proposed an adaptive impedance control strategy for the end-effector trajectory tracking of a flexible robot arm with parametric uncertainty. He has used an adaptive impedance control strategy for flexible manipulators using an end-effector trajectory control scheme.

More recently, Filaretov et al.²⁸ have suggested an adaptive force/position control for robotic manipulators. Unlike, Siciliano et al.⁸⁹, they do not employ force

feedback. They decouple actuator dynamics from the robot dynamics by having a sub-control system, to accurately control actuator dynamics.

5.1. RL Based Compliance schemes

Reinforcement learning compliance control has been a field of interest for researchers for many years now. For example, Kuan *et al.*⁵⁶ have proposed a reinforcement learning mechanism in combination with a robust sliding mode impedance controller for compliance tasks and tested this approach in simulation. A reinforcement learning mechanism is used in their work to deal with the variation in the different compliance tasks. More recently, Kim *et al.*⁴⁸ have used the reinforcement learning approach to find suitable compliance for different situations through interaction with the environment. The effectiveness of the RL based impedance learning scheme by Kim *et al.* has been shown in simulation only. Recent work by Buchli and Schaal¹⁶ proposes reinforcement learning based on the policy improvement with a path integral approach for variable impedance control. However, again the effectiveness was demonstrated in simulation only. In our recent work⁴⁴, we experimentally implement an RL based model reference Cartesian compliance control scheme for a two link robot arm.

6. Human-Robot Interaction Using Compliance

As mentioned earlier, compliance control is usually a good choice in pHRI, to help in solving some safety problems³ (see also Aslam *et al.*¹² for a good review on safe pHRI). One of the interesting examples of using control for human-robot co-operation has been reported by Kumar *et al.*⁵⁸. The proposed method has been demonstrated with a robotic system for a micro-surgical manipulation system. The system has the capability to deal with the nonlinear compliant environment, e.g. living retinal tissues.

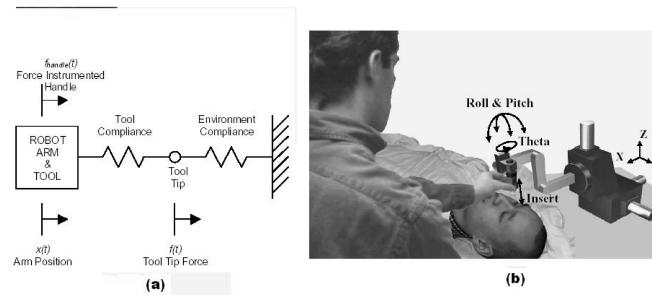


Fig. 17: (a) 1-DOF force control problem (b) steady-hand micro manipulation concept as applied to retinal microsurgery⁵⁸.

Rahman *et al.*⁷⁸ have investigated the impedance of a human arm for the devel-

opment of robots to cooperate with humans. Human muscles have been modelled as a spring-damper system. A second order equation has been used to represent the dynamics of the arm. Position and force data have been used to calculate the impedance parameters.

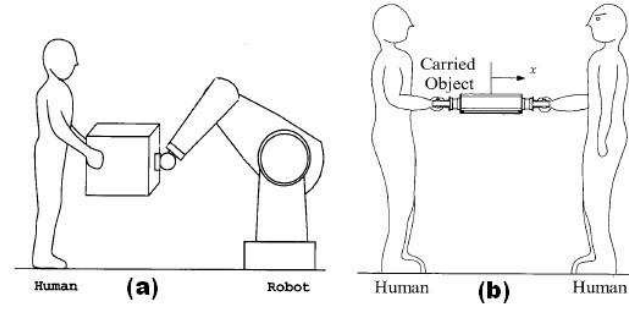


Fig. 18: (a) Human-robot cooperation (b) human-human cooperation ⁷⁸.

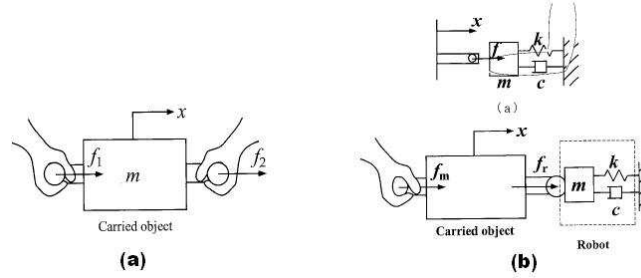


Fig. 19: (a) Model of the 1-DOF carrying task (b) model of the human characterized cooperative robot ⁷⁸.

Tsmugiva et al. ⁹⁵ have proposed a variable impedance control for a human-robot cooperative task (calligraphy). The scheme is based on the estimation of the human-arm stiffness. They are convinced that impedance control based on position control (for human-robot cooperation) becomes unstable when the human subject increases the stiffness of his/her arm or body. This instability has been linked to the time delay of the human or robot movement. The suggested method estimates the stiffness of the human arm on the basis of the data coming from the force sensors of the robot. Adjustment of the parameters is made accordingly in order to overcome instability in the system.

Grunwald et al. ³⁴ have suggested programming the robot arm by touching. The flexibility of the arm is achieved using impedance control. The overall scheme

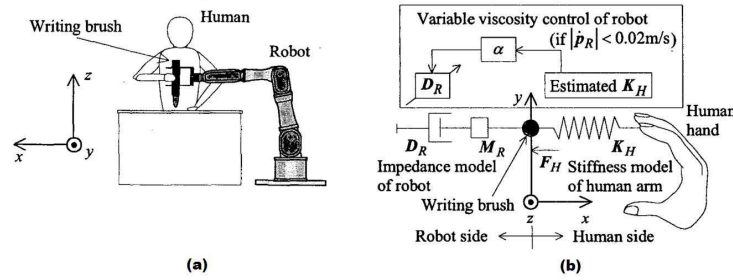


Fig. 20: (a) Human-robot cooperative calligraphy (b) impedance model of human and robot in Cartesian plane ⁹⁵.

is shown in Figure 21.

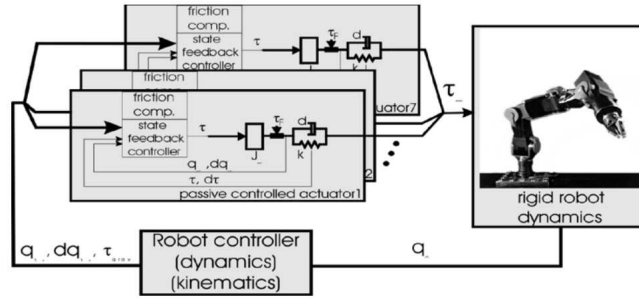


Fig. 21: State feedback controller with gravity compensation ³⁴.

Kasuge and Hirata ⁵³ have reported different types (a mobile robot (MR) helper and distributed robot (DR) helper) of mobile robots for assisting humans in day to day tasks such as lifting or carrying objects from one place to another. Impedance control has an important role to play in such interactions.

Edsinger and Kemp ²⁷ have done interesting work in human robot cooperative tasks such as object passing. As object passing tasks are a key to human robot cooperation, this work investigates such an interaction between robot and human. They have done various cooperative experiments in which the robot helps the user in putting objects on a shelf and holding a box within which the user places objects etc. Their robot uses passive compliance as well employing serial elastic actuators to deal with the safety issues in pHRI.

Recently, Schiavi et al. ⁸³ have used the combination of active compliance and passive compliance for human-robot interaction. Ahmed and Kalaykov ¹ have proposed a semi-active compliance robot to handle safety issues during collision in human-robot interaction.



Fig. 22: (a) Mobile robot (MR) helper (b) distributed robot (DR) helper ⁵³.



Fig. 23: One trial of give and take experiment between robot and human ²⁷.

Yang et al. ¹⁰⁵ have proposed human-like learning controller for compliant interaction with unknown environment. The scheme is inspired by the control action taken by human central nervous system during physical interaction tasks. They claim that the controller can handle instability in interaction by adapting force and impedance in the feed forward manner without the knowledge of the interaction dynamics with the environment. The scheme does not employ any force/torque sensor. This scheme is a good example of the prevailing trend in modern bio-inspired control schemes in robotics. The proposed scheme has been successfully demonstrated using simulation and real robot experiments.

7. Recent trends in compliance Control

As mentioned before, the interest in compliance control, both active compliance and passive compliance (including the recent soft robotics field) is growing rapidly. Robotics researchers are generally convinced that compliance control is very important in resolving safety issues ^{40 11 75 63 76 35 32 96 33 2155 54 52 42 62 105 51}

Majidi ⁶⁴ and others have recently strongly advocated is a bio-inspired soft robotic structures made from deformable matter. This is a new emerging area of robotics ³⁹ primarily aimed at robot designed for interacting with internal organs and skin ⁶⁴. Soft robotics is a bio-inspired area in robotics which will bring new dimensions to robotics.

Hence, the focus is now on a more versatile and hybrid approach to combine passive (including the recent soft) and active compliance approaches to produce variable compliance for HRI ^{59 91 97 98 98 99}. The research in compliant actuation

has gained a lot of popularity¹⁵⁻²⁵. The new generation of robots should have a passive structure to some extent and should be equipped with force/torque sensors and a network of pressure sensors on the body. This will allow to incorporate active compliance techniques to vary the compliance for safety and to perform daily tasks in the human society. At the moment there is no single answer to the safety problem. However this will be a positive step in the right direction.

In this paper, so far a literature review related to active compliance, passive compliance, adaptive compliance and compliance application in pHRI is carried out. A brief review of RL based compliance is also included. It is emphasized here that most of the work in the area of force control or its variants in the beginning, i.e. 70s and 80s, was aimed at solving shop-floor industrial problems such as polishing or grinding surfaces, or assembly operations such as inserting one part into another. Active compliance schemes and hybrid force/position control schemes were investigated for stiff and rigid industrial robots. In the 90s and onward the focus shifted to intrinsic or passive compliance capabilities of robots. In the last decade or so, the interest in compliance control and passively compliant robots and structures became the centre of interest to overcome safety issues in human robot interaction. A new generation of passive actuators, such as artificial muscles and cable driven mechanisms, are now gaining popularity. There is no doubt that passively compliant robot arms are much safer than rigid ones. However, they are mechanically complex and hence, difficult to design and manufacture. A robot arm with too much passive compliance might lose the capability to properly manipulate objects. Such robots may not be suitable for tasks where position accuracy and effort is required.

As mentioned before, for human robot interaction, the robots should have a degree of flexibility or passive compliance but should also be equipped with extra force sensing capability for active compliance control implementation which can be motivated to suit a changing task environment.

8. Conclusion

This paper presented a literature review and highlighted recent advances in compliance control. Active compliance control has been researched for more than thirty years. However, initially, it was mainly aimed to solve industrial problems such as grinding, polishing and pig-and-hole type of problems. With the emergence of humanoid robots and social robotics, the importance of compliance control has increased due to its high relevance with safety in human-robot interaction. Early work on compliance control was mainly focused on model based approaches, on force/torque feedback and mimicking the behaviour of mass spring damper system. Later, dynamic model free adaptive compliance were also developed. In recent years, roboticists realised that active compliance control cannot solve safety problem alone. Hence, intrinsically compliant robotic systems were introduced. However, the need for active compliance is still there. In recent research, a combination of both, active and passive compliance, is considered to solve safety issues in HRI. More recently

there is a new field of soft robotics dealing with the studies of deformable materials. The passive nature of human and animal bodies and the capability to adjust their stiffness according to the situation, makes them very successful in physical interaction with their environment. Hence, it may be concluded here that a degree of passive compliance and a combination of active compliance using torque/force sensors driven by an intelligent control strategy appear to a more suitable solution to achieve variable compliance scheme. Hence, more work is needed on the design of robots as well as active compliance schemes, to help in achieving safety goal in HRI.

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